

# Are galaxies shy ?

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**Abstract.**

## 1. Introduction

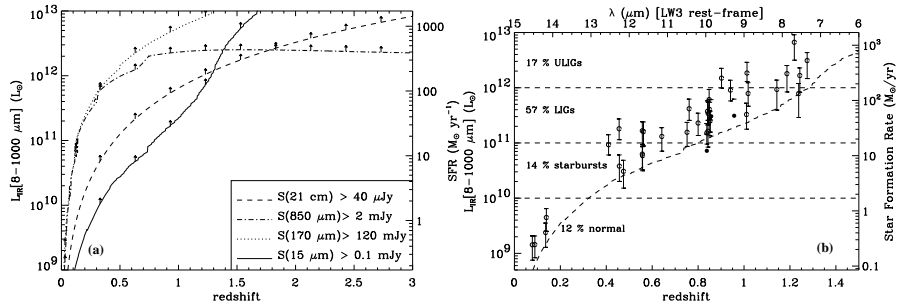
Until 1996, there was little evidence that most galaxies were “shy”, i.e. that they would hide their stars behind a veil of dust and turn red when forming stars, radiating the bulk of their luminosity in the infrared (IR) at a given epoch of their history. Ten years before, IRAS had unveiled a population of luminous IR galaxies exhibiting such a “shy” behavior, the so-called LIGs and ULIGs (with  $12 \geq \log_{10}(L_{\text{IR}}/L_{\odot}) \geq 11$  and  $\log_{10}(L_{\text{IR}}/L_{\odot}) \geq 12$  respectively), which are responsible for the shape of the bolometric luminosity function of local galaxies above  $\sim 10^{11} L_{\odot}$  (Sanders & Mirabel 1996). But integrated over the whole local luminosity function, LIGs and ULIGs only produce  $\sim 2\%$  of the total integrated luminosity and overall only  $\sim 30\%$  of the bolometric luminosity of local galaxies is radiated in the IR above  $\lambda \sim 5 \mu\text{m}$ . The discovery of an extragalactic background in the IR at least as large as the UV-optical-near IR one, the so-called cosmic infrared background (CIRB), with the COBE satellite (Puget et al. 1996, see references in Elbaz et al. 2002b) implied that shyness must have been more common among galaxies in the past than it is today. This was confirmed with the detection of an excess of faint mid IR (MIR) galaxies by ISOCAM onboard ISO (Elbaz et al. 1999), as well as in the far IR (FIR) with ISOPHOT onboard ISO (Dole et al. 2001) and in the sub-millimeter with SCUBA at the JCMT (see Smail et al. 2001). This excess is relative to expectations based on galaxies in the local universe. It implies that galaxies were more luminous in the IR regime and/or more numerous in the past (Chary & Elbaz 2001, Franceschini et al. 2001).

## 2. Mid infrared as a star formation indicator

Chary & Elbaz (2001) and Elbaz et al. (2002b) demonstrated that the MIR luminosity of local galaxies is correlated with their integrated IR luminosity (8-1000  $\mu\text{m}$ ). Hence MIR flux densities can be converted into



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*Figure 1. a)* IR luminosity (left axis) and SFR (right axis) corresponding to the sensitivity limits of ISOCAM ( $15 \mu\text{m}$ , plain line), ISOPHOT ( $170 \mu\text{m}$ , dotted line), SCUBA ( $850 \mu\text{m}$ , dot-dashed line) and VLA/WSRT ( $21 \text{ cm}$ , dashed line, using the radio-FIR correlation) as a function of redshift. K-correction from the library of template SEDs from Chary & Elbaz (2001). *b)*  $L_{\text{IR}}[8-1000 \mu\text{m}]$  and SFR versus redshift and  $\lambda_{\text{rest-frame}}$  for the HDFN galaxies detected above a  $15 \mu\text{m}$  completeness limit of 0.1 mJy (dashed line). Filled dots: 5 AGNs (left axis only).

$L_{\text{IR}}$  and used to compute star formation rates (SFR). The sensitivities of the deepest surveys performed in the MIR ( $0.1 \text{ mJy}$  at  $15 \mu\text{m}$ ), FIR ( $120 \text{ mJy}$  at  $170 \mu\text{m}$ ) and sub-millimeter ( $2 \text{ mJy}$  at  $850 \mu\text{m}$ ) with ISOCAM, ISOPHOT and SCUBA and in the radio ( $40 \mu\text{Jy}$  at  $1.4 \text{ GHz}$ , i.e.  $21 \text{ cm}$ , with the VLA and WSRT) to IR galaxies are compared in Fig. 1a as a function of redshift (see also Elbaz et al. 2002b). Fig. 1a shows that ISOCAM was the most sensitive instrument among the four selected and that it was able to detect nearly all luminous IR galaxies below  $z \sim 1$ . A similar result is obtained using either the proto-typical spectral energy distribution (SED) of M 82 or the library of 100 template SEDs from Chary & Elbaz (2001) constructed to reproduce the correlations between MIR-FIR and sub-millimeter luminosities of local galaxies.

An indication that the SEDs in the IR of distant galaxies resemble local ones comes from the distant “clone” of Arp 220 serendipitously discovered in the field of a QSO (PC 1643+4631). This galaxy, HR10 ( $z = 1.44$ ) known as an extremely red object (ERO) was detected in the radio, MIR and sub-millimeter with a SFR around  $1000 M_{\odot} \text{ yr}^{-1}$  (see Elbaz et al. 2002a and references therein).

The spatial resolution (4 arcsec PSF FWHM) of ISOCAM provided the possibility to identify rather easily optical counterparts to these galaxies and to determine their redshift. Due to limited telescope time allocation, their redshift distribution was inferred from a sub-sample of galaxies in the Hubble Deep Field North (HDFN, Aussel et al. 1999) and their luminosities and star formation rates are presented in the Fig. 1b. About 75 % of the galaxies brighter than about  $0.1 \text{ mJy}$  at  $15 \mu\text{m}$ , and responsible for the steep slope of the number counts, belong

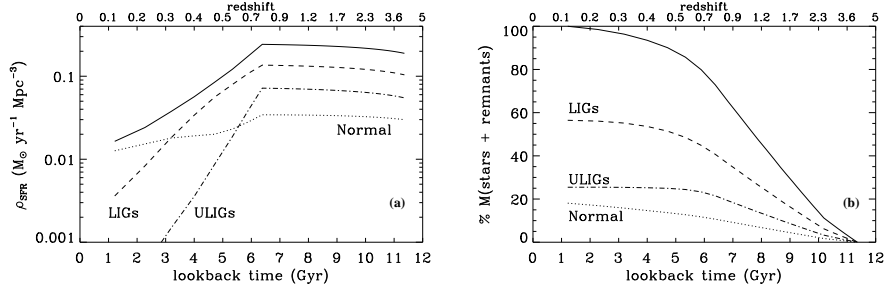


Figure 2. **a)** Cosmic density of star formation as a function of lookback time and redshift from Chary & Elbaz (2001). **b)** Fraction of present-day stars (+ remnants) formed as a function of lookback time and redshift for the scenario of Fig. 2a. Stellar lifetimes (for  $Z_{\odot}$ ): Bressan et al. (1993). Remnant masses: Prantzos & Silk (1998).

to the class of LIGs ( $\sim 55\%$ ) and ULIGs ( $\sim 20\%$ ). Their redshifts spread over the  $z = 0.5$ - $1.3$  range with a median around  $\bar{z} = 0.7$ - $0.8$ .

The fraction of IR light produced by active nuclei was computed from the cross-correlation of ISOCAM with the deepest X-ray surveys from the Chandra and XMM-Newton observatories in the HDFN (41 MIR galaxies) and Lockman Hole (103 MIR galaxies) respectively. Less than 20 % of the ISOCAM galaxies appear to be dominated by an AGN at  $15 \mu\text{m}$  ( $(12 \pm 5)\%$  in the HDFN and  $(13 \pm 4)\%$  in the Lockman Hole, see Fadda et al. 2001).

### 3. On the shyness of galaxies

The MIR-FIR correlations observed in the local universe (Elbaz et al. 2002b) can be used to compute the contribution of the luminous IR galaxies unveiled by ISOCAM below  $z \sim 1.5$  to the CIRB. Elbaz et al. (2002b) computed a contribution of  $(16 \pm 5) \text{ nW m}^{-2} \text{ Hz}^{-1}$  as compared to the peak value of the CIRB of  $(25 \pm 7) \text{ nW m}^{-2} \text{ Hz}^{-1}$  measured with COBE at  $\lambda \sim 140 \mu\text{m}$ . Hence luminous IR galaxies below  $z \sim 1.5$  are responsible for the bulk of the CIRB. Since the CIRB contains most photons radiated by galaxies over the history of the universe, this means that luminous IR galaxies represent a common phase for galaxies. Chary & Elbaz (2001) have studied the range of possible parameters for the evolution of galaxies in luminosity and density over the history of the universe, that would fit number counts from ISOCAM, ISOPHOT and SCUBA as well as the CIRB and the redshift distribution of ISOCAM galaxies. The major result of this study is that although a level of degeneracy remains in the choice of the parameters ruling the evolution of galaxies, existing observations

set a strong constraint on the relatively recent ( $z < 1.5$ ) evolution of the number and luminosity density of luminous IR galaxies. The best fit is obtained for the cosmic history of star formation shown in the Fig. 2a, where the relative roles of ULIGs, LIGs and “normal” galaxies are differentiated. Fig. 2a implies that we are living at an epoch when “normal” galaxies ( $L_{\text{bol}} < 10^{11} L_{\odot}$ ) contribute dominantly to the global star formation activity in the local universe, whereas above  $z \sim 0.3$  the reverse was true: the bulk of the cosmic density of star formation was due to luminous IR galaxies. Hence galaxies in general must have experienced a period of shyness, such as local LIGs and ULIGs, when they formed the bulk of their present-day stars. Fig. 2b represents the fraction of present-day stars plus remnants formed as a function of lookback time or redshift for a given IMF (here from Gould et al. 1996). The total mass is comparable to the local density of baryons in the local universe ( $5 \pm 3 \times 10^8 M_{\odot} \text{ Mpc}^{-3}$ , Fukugita et al. 1998). The error bar on the computed stellar mass is as large  $\sim 50\%$  (including the conversion from MIR to FIR and FIR to SFR), but this result suggests that the bulk of present-day stars formed at a time when their host galaxies experienced such a phase of shyness 5 to 10 Gyr ago, i.e. between  $z = 0.5$  and 2 for an age of the universe of 12.6 Gyr in our cosmology ( $H_0 = 75 \text{ km s}^{-1} \text{ Mpc}^{-1}$ ,  $\Omega_{\text{matter}} = 0.3$ ,  $\Omega_{\Lambda} = 0.7$ ). The shyness of galaxies seems to be the result of galaxy encounters since all ISOCAM galaxies in the HDFN are either merging or members of small groups of galaxies (see Aussel, in this conference). The fact that the CIRB peaks around  $\lambda \sim 140 \mu\text{m}$  was already an indication that it must originate from this redshift range since galaxies SEDs peak above  $\lambda \sim 60 \mu\text{m}$ .

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